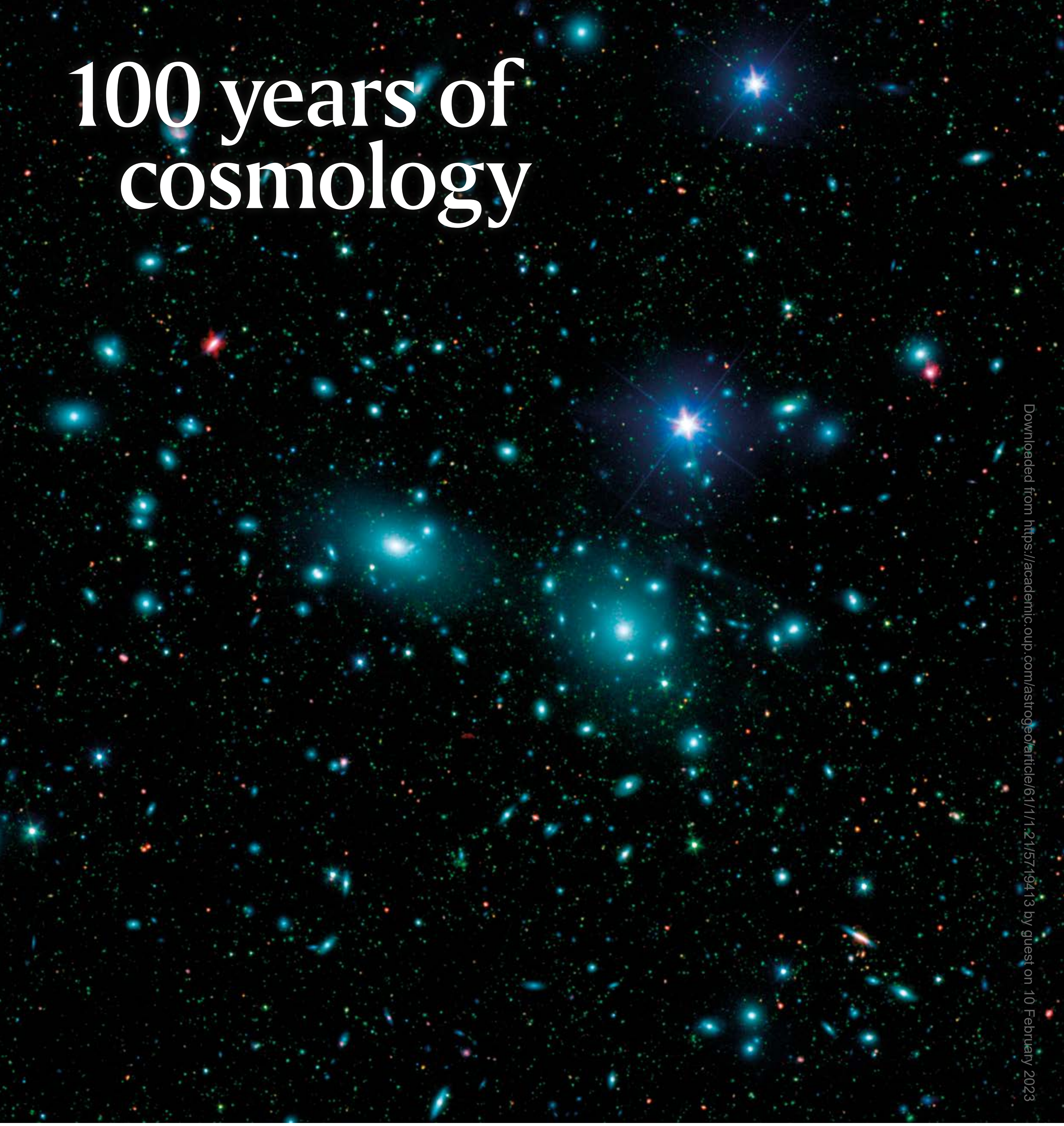
100 years of cosmology



1 *Many of the faint green smudges in the central region of the Coma cluster are dwarf galaxies. In 1933, Fritz Zwicky's mass estimates produced an unexpectedly high mass-to-light ratio for the cluster, marking the beginning of dark matter investigations.* (NASA/JPL-Caltech/L Jenkins [GSFC])

Malcolm Longair describes the development of a subject that was little better than science fiction 200 years ago when the RAS was founded, to our present understanding of the origins of what we see on the largest scale in the universe today – a triumph of experimental, instrumental, observational and theoretical astronomy.

The tremendous progress made in converting cosmology from a purely speculative venture into a rigorous quantitative scientific discipline has been the result of multiple interactions between cognate scientific disciplines – astronomy, astrophysics, physics, chemistry, instrumental and telescope technology, computation and so on. These interdisciplinary interactions are the prime source of the success of cosmology over the past 100 years.

By 1820, astronomy had established itself as the most exact of the physical sciences, the principal role of the national observatories being the precise determination of time and latitude for navigational purposes. Astronomy was largely concerned with the motions of visually observable objects within the solar system relative to the background of "fixed stars". The foundation of the Royal Astronomical Society in 1820, with its first titular president Sir William Herschel, was timely. In 1817, Joseph Fraunhofer published his remarkable high-resolution spectrum of the Sun and then proceeded to take optical spectra of the planets and the brightest stars. In 1838, Friedrich

Table 1 *Discoveries and innovations in astronomy, astrophysics, cosmology and physics from the 1880s to 1920, and the countries in which these were made. The nationalities of the pioneers are not necessarily the same as the countries in which the breakthroughs were made and these are indicated as [1] New Zealander, [2] German, [3] Danish. Advances in physics are shown in blue. The dates are "indicative dates", generally the date of publication of the research, but occasionally the year in which the advance was made is given, if publication was delayed. Occasionally, it refers to the mean date when the research was carried out.*

Table 1 Progress from the 1880s to 1920

discovery/event	date	persons involved
formulation of Boltzmann–Gibbs statistics	1880–90s	Ludwig Boltzmann, Austria; Josiah Willard Gibbs, USA
validation of Maxwell's equations	1887	Heinrich Hertz, Germany
Michelson–Morley experiment	1887	Albert Michelson & Edward Morley, USA
foundation of the *Astrophysical Journal*	1895	George Ellery Hale & James Keeler, California, USA
beginning of construction of the 100-inch telescope	1900s	George Ellery Hale
black-body radiation and the discovery of quantization	1900	Max Planck, Germany
Harvard sequence of stellar spectra	1901	Annie Cannon, Cambridge, Mass., USA
radiative transfer of energy in stars	1902	Ralph Sampson, UK; Arthur Schuster, Manchester, UK; Karl Schwarzschild, Göttingen, Germany
age of the Earth by radioactive dating	1904	Ernest Rutherford, McGill University, Canada [1]
discovery of quanta	1905	Albert Einstein, Switzerland [2]
special theory of relativity	1905	Albert Einstein, Switzerland [2]; Hendrik Lorentz, Netherlands; Henri Poincaré, France
Emden gas spheres – polytropes	1907	Robert Emden, Munich, Germany
validation of the molecular hypothesis	1907	Jean Perrin, France
discovery of white dwarfs	1910	Edward Pickering & Williamina Fleming, Cambridge, Mass., USA; Henry Norris Russell, Princeton, USA
measurement of stellar masses and diameters	1912	Henry Norris Russell & Harlow Shapley, Princeton, USA
period–luminosity relation for Cepheid variables	1912	Henrietta Leavitt, Cambridge, Mass., USA
discovery of cosmic rays	1912	Victor Hess, Graz, Austria
Hertzsprung–Russell diagram	1914	Hans Rosenberg, Göttingen, Germany; Ejnar Hertzsprung, Potsdam, Germany [3]; Henry Norris Russell, Princeton, USA
general theory of relativity	1915	Albert Einstein, Germany
mass–luminosity relation for stars	1915	Jacob Halm, Cape Observatory, South Africa; Ejnar Hertzsprung, Potsdam, Germany [3]
Einstein's static model of the universe – cosmological constant	1917	Albert Einstein, Germany
Shapley's model of the galaxy using globular clusters	1918	Harlow Shapley, Harvard Observatory, USA
gravitational deflection of light by the Sun	1919	Arthur Eddington, Cambridge, UK
nuclear fusion as the energy source of the Sun	1920	Arthur Eddington, Cambridge, UK

Bessel published the first trigonometric parallax of a bright star, 61 Cygni, and the slow process of accumulating stellar distances began. The invention of photography in 1838–39 was quickly assimilated into the armoury of astronomers by pioneers such as John Herschel.

William Herschel had already published his first model of the universe of stars, what we would now call our galaxy, in 1785, with the Sun close to the centre of a flattened stellar distribution. In the course of this work, he, his sister Caroline and his son John began the systematic cataloguing of the diffuse nebulae. The nature of the nebulae was not understood. Some insight was provided in the 1860s by the pioneering optical spectra obtained photographically by William Huggins, who established that some of these had spectra resembling those of stars, while others displayed the characteristic emission lines of hot gases.

Telescope and instrument technology was advancing rapidly. For astronomical imaging, the refracting telescopes of Galileo were superseded by reflecting telescopes, the precursors of the large astronomical reflectors that enabled the nature of the white nebulae to be understood in the early 20th century. The groundwork had been laid for what would become the tools of astrophysical cosmological research, but the first 100 years of the RAS was too early for cosmology to be considered a genuinely observational or theoretical discipline.

Nonetheless, the years up to 1920 were a period of very significant advances in the physical and astronomical sciences. Table 1 contains a list of major discoveries and events in physics and astronomy to 1920. The table includes their indicative dates, the scientists involved and the countries in which research was carried out. The table shows how the main thrust of astronomical achievement was observation, with the beginnings of the application of astrophysical concepts to the study of the stars. Symbolic of what was to come was the foundation of the *Astrophysical Journal* in 1895. The international nature of these achievements made the foundation of the International Astronomical Union in 1919 a key initiative in bringing together what was already an international effort. Technologically, the innovations were dominated by developments in telescope and instrument design. The commissioning of the 100-inch Hooker telescope at Mount Wilson in 1917 represented the state-of-the-art in large telescope design and it was to play a dominant cosmological role in the coming decades. Photographic plates were the recording elements for imaging and spectroscopy. The term "computers" meant people who analysed all types of astronomical–astrophysical data, the most famous example being the remarkable team assembled by Edward Pickering to put order into the massive databases of stellar spectra they had assembled.

1920 to 1939

Many major advances were made during the inter-war years, sowing the seeds for what was to come. My selection of astronomical and cosmological discoveries are listed in table 2. The entries highlighted in blue are

Table 2 1919–1939

discovery/event	date	persons involved
Saha equation	1921	Megh Nad Saha
interferometric measurement of diameters of red giants	1921	Albert Michelson, USA
photoexcitation and photoionization of interstellar gas	1921	Russell (1921), Menzel (1926), Stromgren (1939)
distribution of stars in the galaxy and the mass density in the disc of the galaxy	1922	Jacobus Kapteyn, the Netherlands
Friedman world models	1922	Alexander Friedman, USSR (1922, 1924)
ionization states of ions in stellar atmospheres	1923	Ralph Fowler, Cambridge & Edward Milne, Oxford, UK (1923–24)
the theory of stellar structure and evolution	1924	Arthur Eddington, Cambridge, UK (1916–24)
discovery of galactic rotation	1925	Bertil Lindblad, Sweden
spiral nebulae are extragalactic systems	1925	Knut Lundmark, Sweden; Edwin Hubble, USA (1920, 1925)
chemical composition of the stars	1925	Cecilia Payne (-Gaposhkin), Harvard, USA [1]
Hubble classification of galaxies and their properties	1926	Edwin Hubble, Pasadena, USA
Eddington–Lemaître world models	1927	Arthur Eddington, Cambridge, UK; Georges Lemaître, Belgium
discovery of the differential rotation of the galaxy	1927	Jan Oort, Leiden, the Netherlands
identification of nebulium lines as forbidden transitions	1927	Ira Bowen, California, USA
the theory of white dwarfs	1929	Wilhelm Anderson, Estonia; Edmund Stoner UK; S Chandrasekhar, India (1929, 1931)
quantum barrier penetration in solar nuclear reactions	1929	Robert Atkinson, USA; Fritz Houtermans, Germany
Hubble and the recession of the nebulae	1929	Edwin Hubble, Pasadena, USA
discovery of interstellar extinction by dust	1930	Robert Trumpler, USA (1930); John Plaskett, John Pearce, Canada (1933); Alfred Joy, USA (1939)
discovery of dark matter in clusters of galaxies	1933	Fritz Zwicky, Pasadena, USA [2]
discovery of the radio emission of the galaxy	1933	Karl Jansky, Bell Laboratories, New Jersey, USA (1933); Grote Reber, USA (1940)
theory of development of large-scale structure in the universe; primordial fluctuation problem	1933	Lemaître (1933); Tolman (1934); Lifshitz (1946)
supernovae and their consequences for astrophysics	1934	Walter Baade, USA [3]; Fritz Zwicky, USA [2]
Robertson–Walker metric	1935	Howard Robertson, Pasadena, USA (1935); Arthur Walker, Liverpool, UK (1936)
discovery of the p–p chain	1936	Robert Atkinson, USA; Hans Bethe, USA; Charles Critchfield, USA
theory of interstellar dust extinction	1936	Schalen (1936); van de Hulst (1949)
discovery of CNO cycle	1937	Robert Atkinson, USA (1931); Carl v Weiszächer, Germany (1937); Hans Bethe, USA (1938)
the structure of red giants	1938	Ernst Öpik, Tartu Observatory, Estonia
upper limit to the masses of neutron stars	1938	Lev Landau, Moscow, USSR (1938); Robert Oppenheimer & George Volkov, USA (1939)
inevitability of collapse to a black hole	1939	Lev Landau, USSR (1932); Robert Oppenheimer & Hartland Snyder, USA (1939)
discovery of extensive air-showers	1939	Pierre Auger, France

Table 2 *Key discoveries/innovations and their indicative dates during the interwar years, 1919 to 1939. Conventions as in table 1. Explicitly cosmological advances are shown in blue. Nationality: [1] British, [2] Swiss, [3] German.*

explicitly cosmological advances, but almost all the topics bear in some way on cosmological issues. For example, the beginnings of the understanding of the origin and evolution of the stars demonstrated the applicability of laboratory physics to the very different physical conditions found in stellar interiors. The rate of transformation of the discipline was startling. As William McCrea wrote to me in 1993: "[People] don't realise that before, say, 1916 astronomers simply had no idea what the inside of a star was like, and had no idea how to find out anything about this. The speed at which Eddington transformed the situation was incredible."

The foundations of modern cosmology were laid through the endeavours of Einstein, Friedman, Lemaître, Eddington, Robertson, Walker and Hubble. Once general relativity was formulated and validated by observation, particularly by the explanation of the advance of the perihelion of Mercury, Einstein realized in 1917 that he had the tools with which to derive the first fully self-consistent model of the universe as a whole. At that time, the recession of the nebulae had not been discovered and so he created a static universe with closed spherical geometry by introducing the cosmological constant Λ. The extragalactic nature of the galaxies was established beyond any doubt in 1925, through Hubble's measurement of the distance of the Andromeda Nebula, M31, using the Cepheid variables as distance indicators.

What are now the standard world models were discovered in the period 1922–24 by the Soviet meteorologist Alexander Alexandrovich Friedman. The key realization was that isotropic world models had to have isotropic space curvature everywhere at a given cosmological epoch. There was no reason why the universe should be static, as shown in Friedman's papers. Georges Lemaître

"When scientists returned to research after the war, they were faced with a plethora of testable alternative models"

and Howard Robertson discovered independently the Friedman solutions of Einstein's equations for uniformly expanding universes. In 1927, Lemaître derived the "apparent Doppler effect where the receding velocities of extragalactic nebulae are a cosmical effect of the expansion of the universe". In 1928, Robertson found the theoretical relation $v = cl/R$, where l is the distance. For nearby galaxies he found the equivalent of a Hubble constant of $500\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

In Hubble's iconic velocity–distance relation of 1929, there are only 24 galaxies, most of the velocities having been measured by Vesto Slipher. Hubble's contribution was in making bold estimates of the distances of the galaxies out to the Virgo cluster using three types of distance indicator: Cepheid variables for nearby galaxies, the brightest stars in galaxies for more distant galaxies, and finally the mean luminosities of nebulae for galaxies in the Virgo cluster. By 1934, Hubble and Humason had extended the velocity–distance relation $v = H_0 r$ to 7% of the speed of light by assuming that the fifth brightest members of rich clusters of galaxies can be used as "standard candles", or distance indicators.

In 1933, Fritz Zwicky made the first dynamical estimates of the mass of the Coma cluster of galaxies (figure 1) and found a mass-to-light ratio of 500 for the cluster as a whole. This was very much greater than the values of about 3 found in our vicinity in the galaxy. This was the beginning of the dark matter story, all subsequent studies having confirmed Zwicky's key result.

The impact of the second world war

The major advances in technology resulting from the second world war effort had a major impact upon all astronomy and astrophysics. Primary among these was the opening up of the whole of the electromagnetic spectrum for observation. Radio astronomy benefited from major advances in radio techniques, while access to rockets enabled observations to be made from above the Earth's atmosphere. The huge contribution made by physics to the war effort resulted in increased funding for science as it was appreciated how much innovative science had played during the war and subsequently for the benefit of society at large. Electronic computation was in its infancy, but the exponential growth in computing power was about to begin with huge impact upon all the sciences. All of these contributed to astronomy and cosmology becoming one of the "big sciences".

But there was also the psychological impact upon the scientists of working at breakneck speed on key military priorities during the second world war. As Bernard Lovell wrote in 1987, the astronomers adopted an approach "utterly different from that deriving from the pre-war environment. The involvement with massive operations had conditioned them to think and behave in ways that would have shocked the pre-war university administrators. All these facts were critical in the large-scale development of astronomy."

In space astronomy, the development of rocket technology opened up opportunities for space astronomy. The German V2 rocket was a remarkable technical achievement led by Werner von Braun, who was to lead the US rocket programme. The RAND report of 1946, led by Lyman Spitzer, outlined future possibilities for space astronomy and proposed a programme of space missions for the 1960s. The launch of Sputnik in 1957 galvanized the US administration into creating the National Aeronautics and Space Administration (NASA) in 1958. This became all the more urgent with Yuri Gagarin's space flight in 1961. The USA had fallen behind the USSR – now the space race began in earnest. Both the USA and the USSR pursued programmes to test general relativity in space. In 1961, Howard Robertson led the NASA Conference on Experimental Tests of General Relativity, and the First Soviet Gravitation Conference was held in the same year in Moscow.

An important subplot to these developments was the symbiosis between defence science and its application for the benefit of astronomy. A spectacular example was the discovery of γ-ray bursts as part of the US programme to monitor atmospheric and space nuclear-test explosions following the 1963 Partial Test Ban Treaty. The Vela 3 and Vela 4 satellites discovered the first of these in 1967, but the results were not published in the open literature until 1973.

Another intriguing example concerns the US KH-11 Kennen high-resolution surveillance satellite and the Hubble Space Telescope. Apparently, the KH-11 Kennen satellite was launched with electro-optical (CCD) detectors in 1976, one year before the approval of the Hubble Space Telescope project. It is suggested that the designers of the KH-11 Kennen satellite adopted concepts from the Space Telescope development programme. The space telescopes are strikingly similar, both employing 2.4 m diameter mirrors. Another key development for astronomy was the fabrication of infrared array detectors, which had been deployed as guidance systems for cruise missiles. In the mid-1980s, these arrays became available to astronomers, with remarkable results once they had been optimized for astronomical observation. All these developments were of critical importance for the advance of astrophysical cosmology.

Immediately post-war

The discovery of the velocity–distance relation for galaxies and the pioneering theoretical activity which accompanied it, particularly the realization that the Robertson–Walker metric described all possible isotropic, homogeneous cosmological models, resulted in several different approaches in addition to the standard Friedman models with zero cosmological constant:

- The Eddington–Lemâitre models were proposed to solve the timescale problem that the age of the Earth was greater than the inverse of Hubble's constant, H_0^{-1}. The inclusion of a positive value of the cosmological constant Λ in Einstein's field equations stretched out the cosmological timescale to resolve the timescale problem. Eddington attached great significance to the value of the cosmological constant Λ and attempted to find relation between his "fundamental theory", the value of Λ and the fine-structure constant which appears ubiquitously in quantum physics.
- Paul Dirac was impressed by various large number coincidences between the relative strength of electromagnetic and gravitational forces and the number of protons in the universe. His reasoning led to the conjecture that the gravitational constant varied with cosmic time, a testable hypothesis. A related model for the variation of the gravitational constant with time appeared in the Brans–Dicke model, in which a scalar field was added to the tensor field of standard general relativity.
- Arthur Milne proposed a cosmological model in which there was distinction between cosmic time and electromagnetic time. The empty Milne model was one of the consequences of his reasoning.
- Perhaps most provocative of all was the proposal of a steady state cosmology by Hermann Bondi, Thomas Gold and Fred Hoyle in 1948 to resolve the timescale problem. This unique model involved the hypothesis that the universe as we observe it preserves the same appearance for all time, despite the cosmological recession of the

Table 3 The 1960s

discovery/event	date	persons involved
stellar structure computations create detailed models of the interior of the stars	1960s	among the pioneers were Henyey, Kippenhahn, Iben & Christy; Germany, USA
Leighton and colleagues measure 5-minute oscillations in the Sun	1960	Leighton *et al.* at Caltech, USA
determination of Hubble's constant and the age of the universe	1960s	Sandage (1960s–80s), USA
semiconductor detectors for infrared astronomy	1961	Johnson 1961; Low 1961; USA
discovery of the Hayashi track	1961	Hayashi (1961), Japan
horizon problem in cosmology	1961	Dicke (1961), USA
extragalactic radio sources and quasars show evidence for cosmological evolution	1961–65	Ryle *et al.* (1961), UK; Schmidt (1965), USA
flatness problem in cosmology	1961	Dicke (1961); Peebles & Dicke (1969); USA
development of Earth-rotation aperture synthesis	1962	Martin Ryle, Cambridge, UK
discovery of X-ray sources and the X-ray background	1962	Giacconi *et al.*, USA
exponential decay of light curve due to radioactive decay	1962	Pankey (1962); Colgate & McKee (1969); USA
discovery of interstellar molecular lines in radio waveband	1963	Weinreb *et al.* (1963), USA
Kerr black hole solutions	1963	Kerr (1963), USA [1]
discovery of quasars	1963	Schmidt (1963), USA[2]
accretion model for the energy source of quasars and active galaxies	1964	Salpeter (1964), USA; Zeldovich (1964), Russia; Lynden-Bell (1969), UK
problem of the cosmic helium abundance, origin of the light elements	1964	Hoyle & Tayler (1964), UK; Wagoner *et al.* (1967), USA
discovery of the cosmic background radiation	1965	Penzias & Wilson (1965), USA
Lyman-α clouds as cosmological probes	1965	Gunn & Peterson (1965), USA; Scheuer (1965), UK
baryon asymmetry problem	1965	Zeldovich (1965), Russia; Wagoner *et al.* (1967), USA
detection of far-infrared sources in the Orion Nebula	1966	Becklin & Neugebauer (1966), USA
theory of superluminal motion	1966	Rees (1966, 1967), UK
development of very long baseline interferometry	1967	Broten *et al.*, (1967), Canada; Moran *et al.*, USA
violent relaxation of galaxies in clusters	1967	Lynden-Bell (1967), UK
baryogenesis: Sakharov's rules	1967	Sakharov (1967), Russia
OSO-III and SAS-2 γ-ray missions detect the galactic γ-ray emission	1968	Clark, Germire & Kraushaar (1968); Fichtel, Simpson & Thomson (1972); USA
discovery of radio pulsars as magnetized rotating neutron stars	1968	Hewish *et al.*, Cambridge, UK
discovery of BL-Lac objects	1968	McLeod & Andrew (1968), Canada
thermal history of the universe, epochs of recombination and reionization	1968	Zeldovich *et al.* (1968), Russia; Peebles (1968), USA
Silk damping	1968	Silk (1968), USA [3]
two-point correlation functions for galaxies	1969	Neyman & Scott (1954), USA; Totsuji & Kihara (1969), Japan; Peebles *et al.* 1970s, USA
Hawking and Penrose singularity theorems	1969	Hawking & Penrose (1969), UK

Table 3 *Key discoveries/innovations during the 1960s. Conventions as in table 1. Nationality: [1] New Zealander, [2] Dutch, [3] British.*

nebulae. To replace the dispersing matter, matter had to be continuously created out of the vacuum.

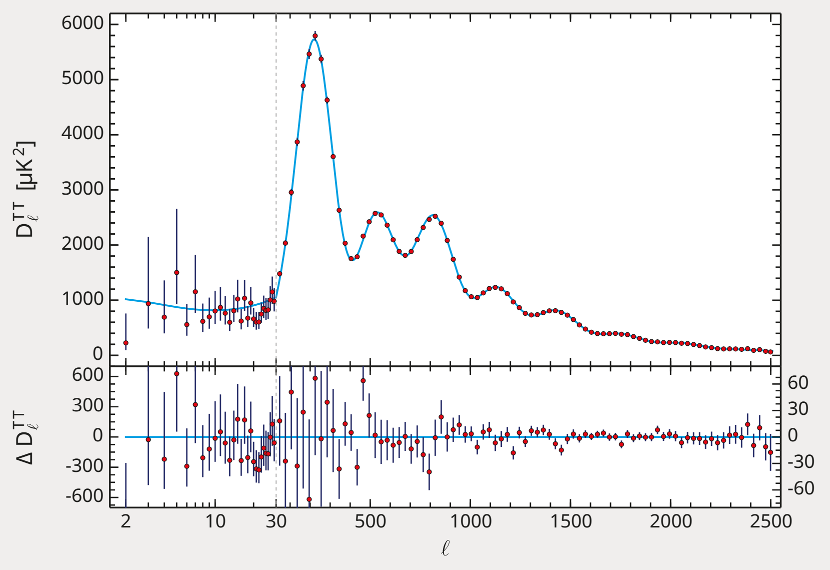
When the physicists and cosmologists returned to pure research after the second world war, they were faced with a plethora of testable alternatives to the standard Friedman models.

The 1960s

It took some time for the potential of the new technologies to be realized, but a flood of innovations and discoveries took place during the 1960s that completely changed the face of astronomical and cosmological research (table 3).

In 1933, radio waves from our galaxy were discovered by Karl Jansky at the Bell Telephone Laboratories. After the war, a number of university groups began to investigate the nature of the cosmic radio emission, led by the physicists who had played a major role in the development of radar during the second world war. The observations soon established the existence of populations of galactic and extragalactic radio sources. In 1951, the brightest extragalactic radio source in the northern sky, Cygnus A, was identified with a very distant galaxy.

In 1963, the radio sources 3C273 was discovered through precise positional measurements with the Parkes telescope in Australia. It was the first radio quasar for which a redshift was obtained, thanks to follow-up spectroscopy by Maarten Schmidt with the Palomar 200-inch telescope. The floodgates opened and within a couple of years quasars with redshifts up to $z=2$ had been discovered. The First Texas Symposium on Relativistic Astrophysics took place in Austin, Texas, in 1963 and these dramatic discoveries were centre stage. The extreme luminosities of the quasars and their rapid variability were



2 *The scalar power spectrum of fluctuations in the cosmic microwave background radiation as observed by the Planck satellite.* (Courtesy of ESA and the Planck Science Team. The Planck Collaboration 2018 arXiv:1807.06209)

unprecedented phenomena in extragalactic astronomy and it was quickly realized that these objects must involve strong gravitational fields. At the closing dinner of the Texas Symposium, Thomas Gold remarked: "Everyone is pleased: the relativists who feel they are being appreciated, who are suddenly experts in a field which they hardly knew existed; the astrophysicists for having enlarged their domain, their empire by the annexation of another subject – general relativity."

The remarkable upsurge of interest in general relativity and cosmology was undoubtedly stimulated by the discovery of radio galaxies and quasars. At the same time, it was demonstrated that the populations of extragalactic radio sources and radio quasars had evolved dramatically with cosmic epoch, contrary to the basic postulate of the steady state model.

In 1966, Antony Hewish, with the assistance of his graduate student Jocelyn Bell (later Bell-Burnell), began construction of a four-acre low-frequency radio array located at the Cambridge Lord's Bridge observatory, to study the "twinkling" of radio sources. Bell was assigned the task of calibrating the array and keeping a weekly track of the scintillating sources over the whole northern sky. In August 1967, a strange source was discovered consisting entirely of scintillations in a region of sky where they were expected to be rather weak. This was the pulsar CP 1919, the first to be discovered. The pulsars were soon identified with magnetized, rotating neutron stars, a key discovery of modern astronomy. Their discovery had implications for understanding all types of explosive events, including the violent events occurring in active galaxies. In the Arecibo surveys for pulsars, the binary pulsar PSR 1913+16 was discovered by Russell Hulse and Joseph Taylor in 1974. Their value as probes of relativistic theories of gravity was immediately appreciated – they provided some of the most stringent tests of general relativity upon which the standard cosmological models are based. All the parameters of the binary orbit could be determined from precise pulsar timing and the energy loss by gravitational radiation, predicted by general relativity, observed for the first time.

The richness of the X-ray sky was revealed with the launch in 1970 of the first survey satellite dedicated to X-ray astronomy, the Uhuru X-ray observatory. The objects detected included active galaxies, clusters of galaxies and compact galactic X-ray sources. The X-ray emission from clusters of galaxies proved to be a key diagnostic for determining the total masses of clusters and of the intracluster gas, as well as providing key cosmological probes. The hot intracluster gas acts as a tracer of the gravitational potential within the cluster and the bremsstrahlung radiation from the hot gas provides an estimate of the total gaseous mass. These observations have provided compelling direct evidence for the presence of about 10 times more dark matter than baryonic matter in clusters of galaxies.

Another spectacular example of the power of combining different techniques to understand the dynamics of the baryonic and dark matter in clusters of galaxies is provided by the system known as the Bullet Cluster, which involves a collision between two clusters. The overall mass distribution of both clusters has been determined by the gravitational lensing of background galaxies and this distribution agrees with the distribution of galaxies. Since these are both composed of "collisionless" particles, they pass through each other. But the diffuse baryonic matter in the clusters suffers a collision which results in the deceleration of these gaseous components and so accounts for the observed difference in location of the gaseous and dark matter distributions. This is sometimes referred to as the "smoking gun" for the dominant presence of non-baryonic dark matter in clusters of galaxies.

The existence of γ-rays of celestial origin was established in 1965 by the Explorer II satellite. In 1972, the SAS-II satellite detected discrete γ-ray sources while the COS-B satellite made the first map of the galactic plane in γ-rays over the period 1975 to 1982. Finally, the Compton Gamma Ray Observatory, which flew in orbit from 1991–2000, made a definitive map of the γ-ray sky and detected many γ-ray bursts. The observation of 2704 γ-ray bursts established that they are uniformly distributed over the sky. Observations of their afterglows at lower energies enabled their positions and redshifts to be measured and established their extragalactic origin. The γ-ray bursts are extremely luminous and last from a fraction of a second to several minutes. They can be observed at very large redshifts and act as probes for studies of the epoch of reionization.

1965–2020: the cosmic microwave background

The discovery of the cosmic microwave background radiation (CMB) by Arno Penzias and Robert Wilson in 1965 was a key event of modern cosmology. They discovered, by accident, background radiation with radiation temperature 3 K in the millimetre waveband wherever they pointed the telescope on the sky. Its thermal spectrum and remarkable isotropy over the sky convincingly demonstrated that they had discovered the cooled remnant of the hot early phases of the universe.

This discovery stimulated a remarkable burst of theoretical and observational studies, in particular working out in detail the thermal evolution of the universe, foreshadowed by the studies of Gamow, Alpher and Herman in the 1940s and 1950s. The studies by Zeldovich, Sunyaev, Peebles and their colleagues disentangled the physics of the epoch of recombination and the necessity of a later epoch of reionization of the intergalactic gas. They also demonstrated how studies of the power spectrum of fluctuations in the CMB could provide crucial evidence about many aspects of cosmology, including the physics of the formation of galaxies and large-scale structures in the universe.

Observations by the Cosmic Background Explorer (COBE) in the 1990s showed that the universe is isotropic to better than one part in 10^5. We need not rehearse the subsequent 50 years of increasingly sensitive and challenging experiment, but leap directly to the remarkable results of the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite, which have measured the properties of the CMB with unprecedented precision, setting a benchmark for contemporary precision cosmology.

Table 4
Cosmological parameters in 2018

baryonic matter	$\Omega_b h^2=0.02233\pm0.00015$
cold dark matter	$\Omega_c h^2=0.1198\pm0.0012$
dark energy	$\Omega_\Lambda=0.6889\pm0.0056$
spatial curvature	$\Omega_K=\Omega_b+\Omega_c+\Omega_\Lambda=0.001\pm0.002$
epoch of reionization	$z_{reion}=7.64\pm0.74$
Hubble's constant	$H_0=100h=67.37\pm0.54\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Table 4 *The final (2018) values of cosmological parameters from the Planck mission.* (The Planck Collaboration 2018 arXiv:1807.06209)

In figure 2, the blue line shows the remarkable agreement between the observed fluctuation power spectrum and the best-fit six-parameter model according to the standard ΛCDM model of structure formation. One of the more dramatic results of the Planck mission is that gravitational lensing of fluctuations in the cosmic microwave background radiation on the last scattering surface at redshifts $z\sim1000$ enables the power spectrum of dark matter perturbations on large scales to be determined. A map has been created of the distribution of dark matter on large scales and the features in it are correlated with the observed distribution of large-scale systems. The result is that the six-parameter family of cosmological parameters can be determined entirely from observations of the CMB.

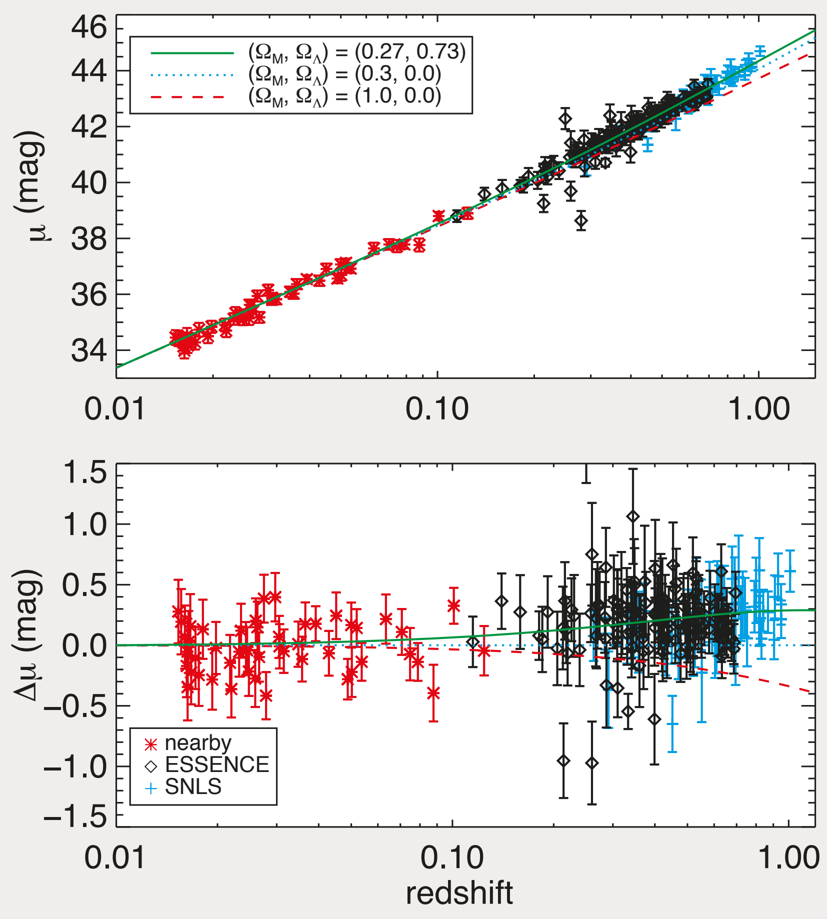
A consistency check is provided by the power spectrum of galaxies on the very large scales at the present epoch as defined by the Sloan Digital Sky Survey. The first peak in the CMB power spectrum is reflected in the correlation function of galaxies on very large angular scales and the corresponding cosmological parameters are in excellent agreement with the value of $\Omega_b h^2$ from the Planck power spectrum.

The large-scale properties of the universe are summarized in table 4. These show that the universe is geometrically flat at the 0.2% level. The values shown in table 4 are undoubtedly rather surprising, but this is what the best observations we have ever made in cosmology are telling us. We live in a universe in which the cosmological constant is finite, and its dynamics are dominated by dark energy and dark matter. The dark matter is a difficult problem and it is perhaps surprising that, despite extraordinarily impressive cryogenic experiments to detect the particles directly and searches for new types of particle with the Large Hadron Collider, they have evaded detection. But, if the dark matter is a difficult problem, the origin of the dark energy is *very* difficult – it only makes its effects observable on large cosmological scales.

The good news is that these estimates of the cosmological parameters are in encouraging agreement with independent estimates. These include:

- acceleration of the universe through the use of Type Ia supernovae
- value of Hubble's constant by independent routes
- mass density of the universe from infall into large-scale structures
- the abundances of the light elements by primordial nucleosynthesis
- age of the galaxy, the ages of the oldest stars and nucleocosmochronology
- the statistics of gravitational lenses.

The demonstration of the acceleration of the universe through the observation of Type Ia supernovae has been a triumph for the classical route to the determination of the kinematics of the universe. As an example, the ESSENCE project had the objective of measuring the redshifts and distances of about 200 supernovae. The observations are consistent with a finite, positive value of the cosmological constant (figure 3). The overplotted green lines are the expected relations for a ΛCDM model with $\Omega_m=0.27$ and $\Omega_\Lambda=0.73$.



3 *The redshift–magnitude relation for Type Ia supernovae from the ESSENCE project.* (K Krisciunas 2008 arXiv:0809.2612)

Why have I given such prominence to the CMB observations? The remarkable aspect of the physics of the primordial perturbation spectrum as reflected in the CMB is that the physics is linear and can be precisely evaluated using well-established physical processes. As a result, the comparison can be made between experiment and observation with a considerable degree of confidence. Now the debate has shifted to the issue of how well the parameters derived from the different routes are in fact in agreement. But we are now talking about discrepancies at less than the 5% level at most – and this is where the next generation of cosmological challenges lie.

I am sure the founders of the Royal Astronomical Society 200 years ago would have been proud that so many of its members have contributed to the extraordinary achievements of the last 100 years. ●

AUTHOR

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FURTHER READING

For more details and references, see Longair (2006) and the recent book *The Oxford Handbook of the History of Modern Cosmology* (2019), edited by H Kragh and M Longair. For a survey of the overall history of astronomy, astrophysics and cosmology over the last 100 years, see Longair (2019), celebrating the centenary of the foundation of the International Astronomical Union. The reader may also find the review by Longair (2001) a helpful survey of the crucial role of advanced technology in making the scientific study of cosmology a reality. More information about the Kennen satellites can be found at en.wikipedia.org/wiki/KH-11_Kennen

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